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Forecasting the groundwater level of cement raw materials deposit based on dynamic neighborhood models*

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Прогнозирование уровня подземных вод месторождения цементного сырья на основе динамических окрестностных моделей***

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Introduction. The development of a mathematical model for the groundwater level of a deposit of cement raw materials located in the Zadonian-Yelets aquifer, which is the principal domestic water supply source for the city of Lipetsk, is considered. Therefore, it is necessary to provide ongoing monitoring and to have the possibility to predict the water level under the field development. The work objectives are the identification and study of a dynamic neighborhood model with variable hierarchical neighborhoods of the groundwater level that enables to adequately predict value of the water level in the examined wells.

Materials and Methods. The definition of a dynamic neighborhood model with variable hierarchical neighborhoods is given, differing by time-varying double-level neighborhood communications between the first- and second-level nodes. At each next discrete instant of time, the neighborhood model nodes change their state under the influence of the online parameters and node states included in their neighborhood. As a subcase, we consider a model with line state recalculation functions. Parametric identification of the dynamic neighborhood model consists in finding the system parameters for each second-level node, and is based on the ordinary least squares.

Research Results. A linear dynamic neighborhood model with variable hierarchical neighborhoods for predicting the groundwater level in a cement raw material deposit located in the Zadonian-Yelets aquifer is developed. The software using C++ is developed for the parametric identification and simulation of the functioning of the dynamic neighborhood model under consideration. It enables to determine parameters of the node state recalculation functions for a given structure,

Введение. Статья посвящена разработке математической модели уровня подземных вод месторождения цементного сырья, расположенного в задонско-елецком водоносном горизонте, являющимся основным источником хозяйственно-питьевого водоснабжения города Липецка. Поэтому на стадии разработки месторождения необходимо проводить постоянный мониторинг и иметь возможность прогнозирования уровня подземных вод.
Цель работы — идентификация и исследование динамической окрестностной модели с переменными иерархическими окрестностями уровня подземных вод, позволяющей с достаточной точностью прогнозировать значение уровня вод в обследуемых скважинах.

Материалы и методы. Приведено определение динамической окрестностной модели с переменными иерархическими окрестностями, отличающейся изменяющимися во времени двухуровневыми окрестностными связями между узлами первого и второго уровня. В каждый следующий дискретный момент времени узлы окрестностной модели меняют свое состояние под воздействием текущих управлений и состояний узлов, входящих в их окрестности. В качестве частного случая рассмотрена модель с линейными функциями пересчета состояний. Параметрическая идентификация динамической окрестностной модели заключается в нахождении параметров системы для каждого узла второго уровня и основана на методе наименьших квадратов.

Результаты исследования. Разработана линейная динамическая окрестностная модель с переменными иерархическими окрестностями для прогнозирования уровня подземных вод месторождения цементного сырья, расположенного в задонско-елецком водоносном горизонте. Для параметрической идентификации и моделирования функционирования рассматриваемой динамической окрестностной модели разработано программное обеспечение на языке C++, позволяющее для заданной

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and also to predict the model behavior in the operation process. A hierarchical structure is given, and a parametric identification of the linear dynamic neighborhood model of the groundwater level is carried out. After the parametric identification on the teaching data selection, the mathematical model is checked on the test sample.
Discussion and Conclusions. The obtained average ratio errors of the identification and forecast suggest the developed model validity and enable to recommend it for predicting the underground water level of a cement raw materials deposit.

структуры находить параметры функций пересчета состояний узлов, а также прогнозировать поведение модели в процессе функционирования. Приведена иерархическая структура и проведена параметрическая идентификация линейной динамической окрестностной модели уровня подземных вод. После выполнения параметрической идентификации на обучающей выборке данных математическая модель проверена на контрольной выборке.
Обсуждение и заключения. Полученные средние относительные ошибки идентификации и прогноза свидетельствуют об адекватности разработанной модели и позволяют рекомендовать ее для прогнозирования уровня подземных вод месторождения цементного сырья.

Keywords: groundwater level, deposit of cement raw materials, dynamic neighborhood model with variable hierarchical neighborhoods, parametric identification.

Ключевые слова: уровень подземных вод, месторождение цементного сырья, динамическая окрестностная модель с переменными иерархическими окрестностями, параметрическая идентификация.

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Introduction. Zadonian-Yelets horizon is the main productive complex of limestone suitable for cement and metallurgical industries [1]. Limestone is light and light gray, with a yellowish tinge, medium-hard, fractured, fine-grained. You can often find hard limestone represented by silicified varieties. Limestone is often porous and cavernous. Clay rocks suitable for cement production lie among the quaternary deposits covering the limestone.

Overburden rocks are represented by a fertile layer of soil, loam, substandard clay, sand and a layer of crushed stone in the upper part of the destroyed limestone.

Hydrogeological conditions of the deposit are simple. Sokolsco-Sitovsky deposit is in in geomorphological terms in the slope part of the valley of the Voronezh River, which determines the hydrogeological situation in the field area [2].

The aquifer is fed by infiltration of atmospheric precipitation and by absorption of flood flow through the valleys of gullies and ravines. Groundwater discharge is in the Voronezh River.

The current position of the groundwater level was studied by monitoring observations in 7 wells evenly located on the field area. The level of groundwater in the low-water period varies from 102.5 m to 109.7 m.

Currently, the Zadonian-Yelets aquifer is the main source of the domestic and drinking water supply of the Lipetsk city. In this regard, the development of limestone can be made only in the water-free part of them with high pillar of at least 2.0 m, which is recommended by the sanitary service of the Lipetsk region.

Water inflow into the developed pit of the deposit occurs only due to atmospheric precipitation. In this regard, at the stage of development of the field, it is necessary to constantly monitor the state of groundwater of the Zadonian-Yelets aquifer and to be able to predict the groundwater level.

Dynamic neighborhood models with variable hierarchical neighborhoods are used in this paper to model the groundwater level of the field under consideration. These models allow modeling complex spatially distributed processes and objects that change their state in time [3-8].

Neighborhood models were first proposed in the late 90-ies of XX century [9]. The basic definitions and algorithms of the theory of neighborhood modeling are given in [9-12]. The concepts of “neighborhood”, “neighborhood communications” are considered in [13-14]. They use agents that move around the neighborhood and interact with each other according to certain rules. Today, the theory of neighborhood modeling is being actively developed. There appeared dynamic [6-8], non-deterministic models [11], models with variable neighborhoods [15].

Materials and Methods. In this paper, we use dynamic neighborhood models to predict the state of spatially distributed systems. In them, each node is an independent object, functioning in time and related by neighborhood communications to the other objects of the system. This distinguishes the models under consideration from the widely used today neural networks, which can be used to simulate the operation of each object or node separately. The method of neighborhood modeling is intended for simultaneous joint modeling and prediction of the behavior of all elements of a distributed system.

Next, we consider the dynamic neighborhood models “input-state” with variable hierarchical neighborhoods. They differ in time-varying double-level neighborhood communications between the first- and second-level nodes, and in line state recalculation functions. They enable, in comparison with the known one-level neighborhood models, to perform forecasting with higher accuracy.

The dynamic neighborhood “input-state” model with variable [15] hierarchical neighborhoods can be specified by the set $NS_{IER} = (N, X, V, G, X[0], t)$, where:

1) $N = (A, O_x, O_v, O_{ier})$ is a two-level structure of the neighborhood model; $A = \{a_1, a_2, ..., a_n\}$ is a set of nodes of the first level; O_x and O_v are neighborhoods of communications of nodes by states and by controls, respectively; O_{ier} are hierarchical neighborhood communications between nodes. Each node $a_i \in A$ has its own neighborhood defined by states $O_x[a_i] \subseteq A$ and controls $O_v[a_i] \subseteq A$; $O_x = \bigcup_{i=1}^{n} O_x[a_i]$, $O_v = \bigcup_{i=1}^{n} O_v[a_i]$.

Some nodes of the first level $a_i \in A$ are assigned a set of nodes of the second level $O_{ier}[a_i] = \{a_i^1, ..., a_i^c\}$. All nodes $a_j \in O_x[a_i]$, $a_k \in O_v[a_i]$ have an impact on the second level nodes $a_i^b \in O_{ier}[a_i]$.

At each point in time, only a single active node is defined $b = 1, ..., c$ such that $a_i^b \in O_{ier}[a_i, t]$.

The node a_i^b is active at the time t if it meets the specified activation condition $f_i^b[t] = \text{true}$. For all nodes of the second level a_i^b $O_x[a_i^b] = O_x[a_i]$; $O_v[a_i^b] = O_v[a_i]$.

2) $X \in R^{\sum_{i=1}^{n} p_i}$ is a block vector of states of the neighborhood model in real time, each block of which $X[a_i] = X[i] \in R^{p_i}$ is a vector of states in the node a_i of the system $i = 1, ..., n$.

3) $V \in R^{\sum_{i=1}^{n} m_i}$ is a block vector of controls in real time, each block of $V[a_i] = V[i] \in R^{m_i}$ is a vector of controls in the node a_i of the system $i = 1, ..., n$.

4) $G : X_{O_x} \times V_{O_v} \to X$ is a vector function of states recalculating of the neighborhood model, where X_{O_x} is a set of states of the nodes of the first level, included in the neighborhood O_x; V_{O_v} is a set of controls of the nodes of the first level, included in the neighborhood O_v.

For the nodes of the first level $a_i \in A$, the function G_i will be:

$$X[t+1, i] = G_i[t] = \sum_{b=1}^{c} X[t+1, i^b] = \sum_{b=1}^{c} G_i^b[t], \qquad (1)$$

where $G_i^b : X_{O_x[a_i^b]} \times V_{O_v[a_i^b]} \to X[i^b]$ is a state recalculation function for the second-level node a_i^b.

For each node of the second level $a_i^b \in O_{ier}[a_i, t]$, the function G_i^b in real time in the linear case has the form:

$$X[t+1, i^b] = \sum_{a_j \in O_x[a_{i^b}]} g_x^b[i^b, j] X[t, j] + \sum_{a_k \in O_v[a_{i^b}]} g_v^b[i^b, k] V[t, k] + g_c^b[i^b], \qquad (2)$$

where $a_j, a_k \in A$ $(j, k = 1, ..., n)$ are nodes of the first level of the model; $X[t, i^b] \in R^{p_i}$ is the state in the node a_i^b at time t; $V[t, i^b] \in R^{m_i}$ is the control in the node a_i^b at time t; $g_x^b[i^b, j] \in R^{p_i \times p_j}$, $g_v^b[i^b, k] \in R^{p_i \times m_k}$, $g_c^b[i^b] \in R^{p_i \times 1}$ are model matrix-parameters.

For each second-level node $a_i^b \notin O_{ier}[a_i, t]$, the function G_i^b is currently zero, that is $X[t+1, i^b] = G_i^b[t] = 0$.

5) $X[0] \in R^{\sum_{i=1}^{n} p_i}$ is the initial state of the model.

6) t is the current discrete time of the model.

The structure of the neighborhood model can be represented as a single two-level graph of the structure of the neighborhood model-oriented graph with two types of arcs: state and control actions — or two-oriented graphs — external and internal structures.

Parametric identification of the dynamic neighborhood model [16-17] is in finding the system parameters for each node of the second level, and it is based on the least squares method:

$$E = \sum_{i=1}^{n} \| X[t+1, i] - G_i[t] \| \to \min.$$

Research Results. Let us consider the linear dynamic neighborhood model of the level of cement raw materials underground waters deposits. Fig. 1 shows the graph of the external structure of the model. Node a_1 is external environment. Currently, 7 wells are used for groundwater level monitoring purposes, which in Fig. 1 correspond to the nodes $a_2 - a_8$. The control actions of the nodes $V[t,i] \in R^{10}$ consist of the amount of precipitation in mm and of the average daily air temperature in °C for the last 5 days before the measurement of the water level in the wells at time *t*. The states of the nodes $X[t,i] \in R$ are equal to the water level in the well *i* at time t , $i = 2,...,8$.

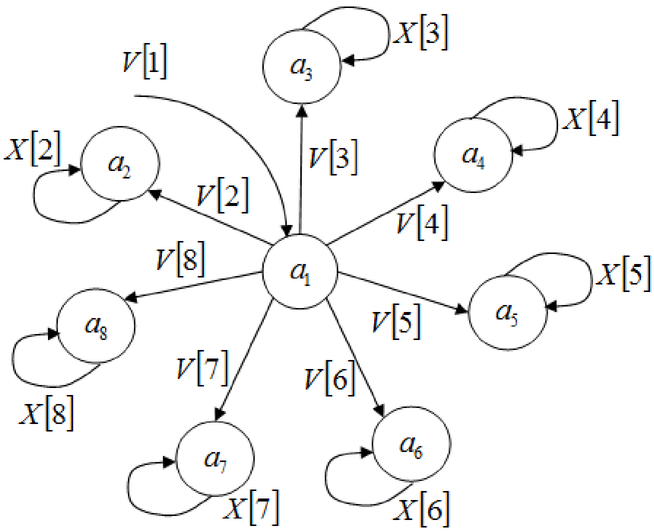

Fig. 1. Graph of the outer structure of the neighborhood model

The first level nodes of the neighborhood model a_i ($i = 2,...,8$) are hierarchical: $O_{ier}[a_i] = \{a_i^1, a_i^2\}$ and correspond to the positive and negative average daily air temperature. Their structure is shown in Fig. 2.

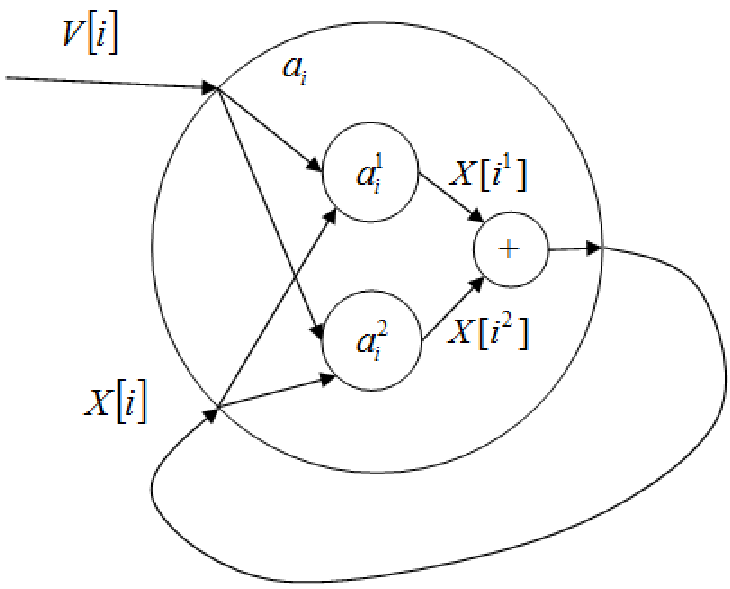

Fig. 2. Graph of the inner structure of the first level nodes

The system (2) for each node of the second level a_i^b of the surrounding groundwater level model will have the following form:

$$X[t+1, i^b] = g_x^b[i, i^b] X[t, i^b] + g_v^b[i, i^b] V[t, i^b] + g_v^b[i^b], \tag{3}$$

where $g_x^b[i,i] \in R$; $g_v^b[i,i] \in R^{1\times 10}$; $g_c^b[i] \in R$; $i = 2,...,8$; $b = 1,2$.

The program in C++is developed for the parametric identification and performance simulation of the considered dynamic neighborhood model. The initial data for identification are the structure and the training sample. The program allows you to find parameters of the recalculation functions of node states, as well as to predict the behavior of the mathematical model in the process of operation.

After the parametric identification on the training data sample, the obtained model was tested on the control sample. The normalized initial and model values of the groundwater level for the node a_2 for training and control sampling are shown, respectively, in Fig. 3 and Fig. 4.

Fig. 3. Normalized source and model values of the groundwater level for the node a_2

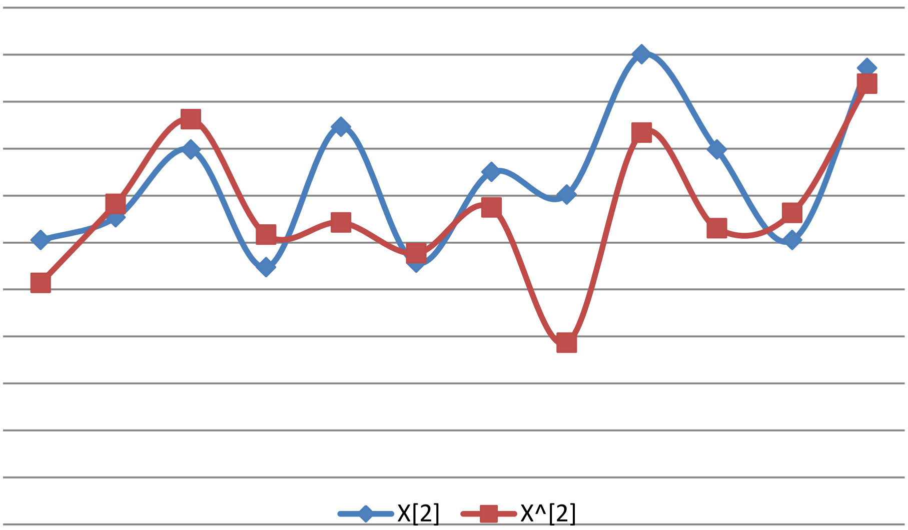

Fig. 4. Normalized source and predicted values of the groundwater level for the node a_2

The average relative error of identification (prediction) of the neighborhood model is calculated by the formula:

$$A = \frac{1}{Mn}\sum_{k=1}^{M}\sum_{i=1}^{n}\left|\frac{\hat{X}_m[t+1,i]-X_m[t+1,i]}{X_m[t+1,i]}\right|\cdot 100\%,$$

where $X_m[t+1,i]$ is the state of the node in the m-th training (control) sample tuple; $\hat{X}_m[t+1,i]$ are model values of the node state a_i; M is the volume of the training (control) sample.

The average relative error of prediction is shown in Fig. 5.

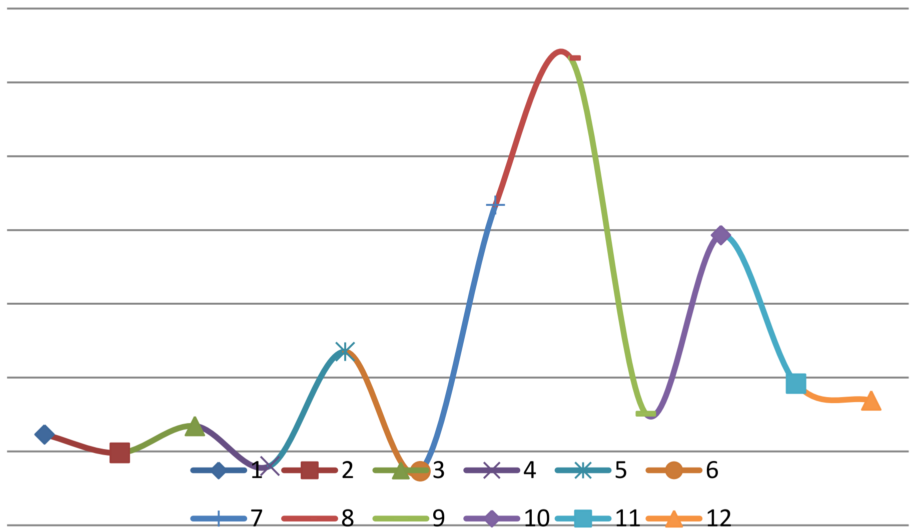

Fig. 5. Average relative prediction error for each tuple of the control sampling

The average relative error of identification was 0.19%, the average relative error of prediction was 0.23%, which indicates the adequacy of the developed model and allows us to recommend it for predicting the level of underground waters of the cement raw material field.

Conclusion. A linear dynamic neighborhood model with variable hierarchical surroundings to predict groundwater level deposits of cement raw materials, located in Zadonian-Yelets aquifer, is developed.

The software in C++programming language is developed for the parametric identification and performance simulation of the considered dynamic neighborhood model.

The implemented model predicts the level of groundwater in the analyzed wells with sufficient accuracy and can be effectively used to predict the level of groundwater deposits of cement raw materials.

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